Analogue versus Digital for Baseband Beam Steerable Array used for LEO Satellite Applications

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Abstract— **This paper presents an implementation of analogue baseband beam steering and its digital counterpart as an attempt to compare between both methods for LEO satellite applications. Both methods are explained, implemented and compared in terms of different aspects such as power consumption, space qualification, flexibility, and speed of steering for a 1×2 prototype.**

I. Introduction

The capabilities of digital technology have been increasing considerably in recent years. This has boosted the use of Digital Beam Forming (DBF) compared to Analogue Beam Forming (ABF). However, what we know today as DBF is actually IF band or baseband DBF, due to the fact that the phase shift between the elements is applied in these bands. On the other hand, ABF, which today is more frequently realized at RF frequencies, can also be performed at IF or baseband frequencies. In this paper, a comparison of Analogue and Digital Baseband Beam forming (ABBF and DBBF) is given [1]. In section II, the difference between baseband, IF and RF beam forming is explained. Section III explains the functioning of the key part of the array, namely the phase shifter. In section IV, the implementation of both a 1 x 2 ABBF and DBBF prototype are discussed. Afterwards, a comparison between both methods regarding price, space qualification, power consumption, size, and speed of steering in LEO space conditions is given. Finally the paper is concluded in section V.

II. Comparison of Analogue RF, IF, and Baseband Beam Forming

As a result of the using of RF phase shifters, RF beam forming has several limitations: primarily high insertion loss, limited phase range, and power consumption.

Alternatively, IF beam forming can also be used. It has the same basics as RF beam forming, but the lower frequency has both positive and negative consequences. Circuit design in general becomes easier, components are more readily available, and circuit losses are lower. On the other hand, delay lines become longer and the required mirror frequency rejection usually is a problem [2], as well as increased inter-symbol interference (ISI).

Direct conversion can be seen as mixing to an IF of 0 Hz. This method eliminates the problems of the image signal and its rejection. A disadvantage of this technique is the need for quadrature conversion to be able to reconstruct the original signal from the baseband signal(s).

III. Phase Shifter in ABBF and DBBF

In principle, proper phase shifts and amplitude modification in each or some of the elements are needed to steer the beam in the desired direction. The block diagram of the phase shifter is illustrated in Fig. 1. This can be done in digital or analogue technology. In DBBF, we use an FPGA device to implement the phase shift digitally. In ABBF, the phase shift is implemented using a simple analogue circuit for each element [1]. This circuit resembles a QAM modulator [2]. The value of $\Delta\theta$ is equal to the phase change and the amplitude is scaled by multiplication with optional coefficients. Finally, the output signals from all phase shifters are summed to form the array output.

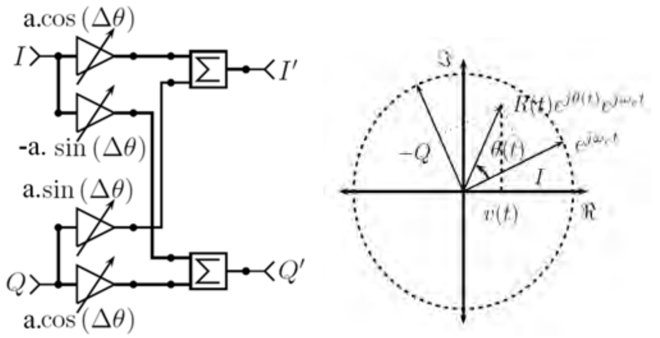


Fig. 1 Phase shifter block diagram and principle.

IV. ABBF versus DBBF

In order to observe the differences between the two methods, two 1×2 array prototypes, using both techniques respectively, were designed. The block diagrams of the designs are presented in Fig. 2. Two circularly polarized microstrip antenna elements working at 2 GHz are used to receive the RF wave. RO4003 has been used as a certified board for space applications [3]. A direct conversion RF circuit from 2 GHz to baseband is used immediately behind the antenna to produce four balanced in-phase and quadrature output components. This part is the same in both prototypes.

An FPGA is the most efficient option for the DBBF baseband part rather than DSP or ASIC, due to its high speed, simplicity, low power consumption, and price. A VHDL code was developed which receives the two digitized I and Q signals from ADCs. Next, the phase shift is applied and the shifted signals are combined and then transferred to the outputs. The schematic of the code is shown in Fig.3.

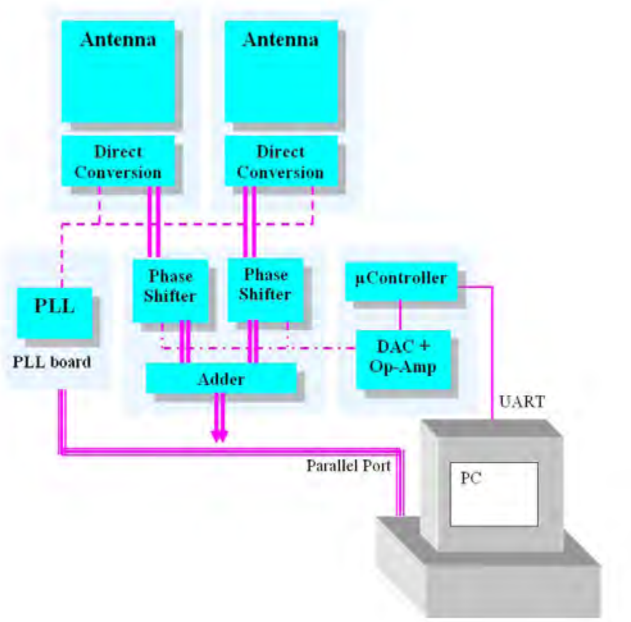
The ABBF implementation is a bit more complex (Fig. 1) and composed of 4 multipliers and 2 op-amps (to sum multiplied signals) per antenna element, and then a combiner circuit plus an ADC at the end. A microcontroller circuit and the DAC (digital to analogue converter) circuit control the phase shifter multiplying voltages.

The physical bandwidth of the antenna element, array factor and RF downconverter can be accommodated by proper baseband processing speeds of nowadays FPGAs. However, when increasing the number of elements, and thus the gain of the array, the processing speed of the FPGAs does become the limiting factor. For instance, having 100 antenna elements and one I and Q channel per element, taking 60 Msamples/s and 10 operations per sample, we end at 120 Giga-operations/s. This is not easily feasible with readily available components. On the other hand, this speed problem is not an issue in the case of analogue systems [4]. Baseband signal processing is very fast if implemented in an analogue way. The only problem there is the bandwidth of the analogue circuits. Therefore, wideband multipliers, op-amps and high data rate ADCs are required.

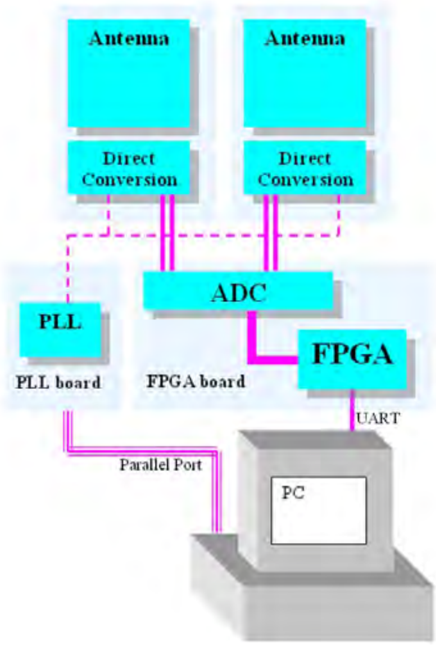
Both prototypes are controlled by a PC that later can be substituted by a satellite's CPU. The ABBF microcontroller is connected to a PC via an UART bus and dedicated MATLAB code steers the beam in any wanted direction. Based on the defined array direction, the code calculates and sends the commands to the microcontroller and the microcontroller hands them out to the proper DAC. Each of the 8 DACs produces the required positive or negative voltage and the corresponding Op-Amp sets the output gain. This combination of the Op-Amp gain and DAC output defines the multiplier value "a" in Fig.1. There are different sources of phase error which make the calibration inevitable, mainly LO phase difference at mixers, different RF line length between antennas and mixers, and none-identical phase shifters.

To calibrate the array, the output level of each antenna path is measured separately setting the phase shift to 0 and the amplification to unity. The calculated phase and amplitude different are considered in the DAC output calculation.

The FGPA board of the DBBF prototype is also connected to the PC via an UART connection on the board, and controlled using MATLAB code. The GUI (graphical user interface of the code is shown in Fig. 4. In the calibration phase the multipliers are set to no phase shift and unity gain. Then the received carrier data from the transmitter is captured. Based on the phase and amplitude difference, the array is calibrated. Then, using the desired beam direction, the multiplier values are defined and sent to the FPGA to set the multipliers of the digital phase shifters. To observe the output, a DAC converts the digital output of the FPGA to an analogue observable signal.



(a) ABBF



(a) DBBF

Fig.2: Schematic of 1×2 prototype design.

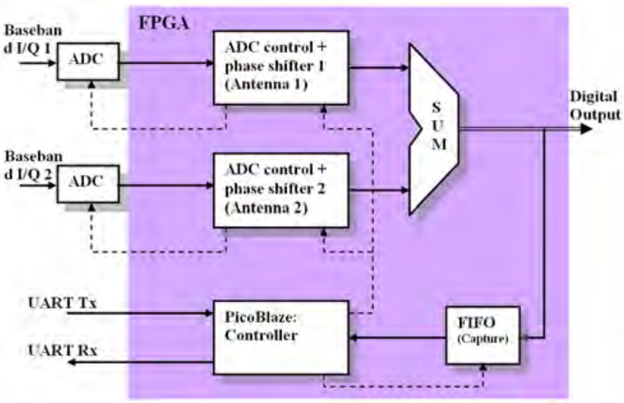


Fig.3: VHDL implementation of a baseband beam former

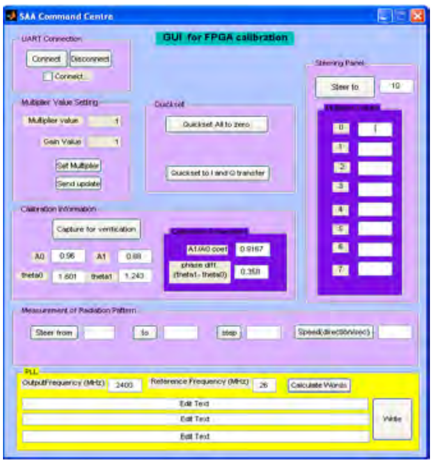


Fig.4: GUI code to control the DBBF array.

V. COMPARISON

The most important factors for an array working in space are space qualification, price, power consumption, size and weight, flexibility, and steering speed. In terms of size (occupied area) and weight, the difference is not significant at low microwave frequencies, especially if the number of elements increases. The reason is that the aperture area is determined by antenna element placement. Both tested prototypes are shown in Fig. 4.

A. Space Qualification and Price

The price of space qualified components is always an issue. When sending electronic equipment into space, the launch and the space environment have to be taken into account [5]. This implies a proper selection of the components in the design [6]. This does not mean that all components in the satellite, regardless of orbit and mission, should be space grade radiation hardened [7]. In many cases COTS (commercial of the Shelf) can be and indeed are used. However, no large volumes are necessary, and thus sometimes this cost is not the primary issue. Using space environment simulation chambers, one can measure the performance of the boards before sending to space. A Cobalt-60 gamma ray source is used for comparative studies on packaged semiconductor integrated circuits for ionising radiation (total dose) effects in [8]. Tests shows that many of the COTS components can also be used in LEO space missions. Thus, from a financial point of view, the advantage is not clear and significant.

For the analogue multiplier, for instance, the only space grade available component is AD534S which costs ten times a none-space grade AD534 counterpart or MLT04 (four analogue multipliers per IC). Space grade FPGAs such as Virtex-4Q and AT40KEL040 are available, but it has been shown that lower grades such as the Virtex-5Q military grade in many cases are able to work.

Although the cost overview highly depends on the grade of the components used, increasing the number of elements, the advantage of DBBF will become more and more evident, due to the fact that the number of costly phase shifters in ABBF increases with the number of elements N.

B. Power Consumption

The most power consuming part of the array is the RF part. More than 650 mW per direct conversion demodulator and 300 mW for the space grade PLL400-2200 board are required while adding a LNA right after the antenna consumes another 900 mW, 3.5 Watts in total.

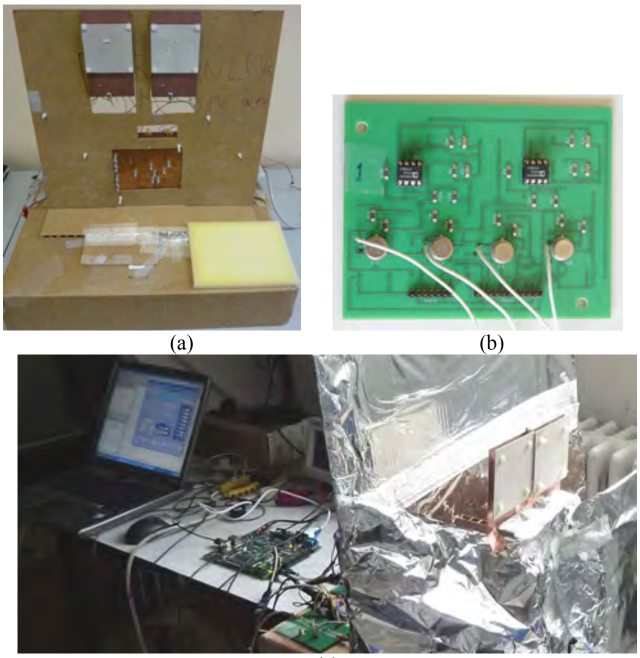
Considering the ABBF, the phase shifter part is quite power consuming. AD534S or AD534 circuits consume approximately 100 mW while a MLT04 consumes only 150 mW for four multipliers. The AD844S circuit as a space grade opamp consumes 200 mW while the TL084, with four opamps per IC, consumes 200 mW. Thus, requiring 8 multipliers and 4 opamps for the whole prototype, the consuming range will be in between 500 mW and 1.6 Watt. Measurements of an space grade phase shifter design, demonstrated n in Fig.5 (a), shows a slightly higher consumption, 1.9 Watt for both phase shifters. In ABBF, a microcontroller and DAC board, including an opamp, are needed with quite high power consumption. On the other hand, in DBBF there is only need for the FPGA and ADC board (4 parallel analogue to digital converters), which are consuming much less, around 500 mW. Therefore, in our design using AD844 and AD534, ABBF is consuming more than DBBF. However, if low power COTS components can be used, ABBF will be as good as DBBF.

Another important point is that, when the number of elements increases, the consuming power of the array after the RF part is $2N\times P_{adc}$ for DBBF, which is normally low power consuming, while it is $2N\times(P_{mult}+P_{opamp}+P_{dac})$ for ABBF. This indeed is a serious advantage of DBBF for larger arrays.

C. Flexibility

As ABBF is using a digital microcontroller to control the beam, it can also be considered hybrid analogue digital baseband beam forming. This certainly makes it somewhat flexible. However, DBBF is basically more flexible due to the implementation of many parts in the FPGA. In both cases, the digital part, namely the microcontroller or the FPGA, can take over the controller completely.

When the array is getting larger and larger the FPGA part in DBBF gradually limits the performance. This is mostly due to the limited number of FPGA output pins, which have to be used simultaneously, and also the limited processing power. A possible solution then is parallel FPGAs. However, this raises new challenges. The problem of limited number of microcontroller output pins may also exist for ABBF. However, they are used only to set the multiplier values and this can be done consecutively in series, although this might not be favourable because it produces transient time beam shapes and decreases the steering speed. To avoid this, an alternate solution is a consecutive hierarchical distribution of microcontrollers [1].



(a) (b)

(c)

Fig.5 :(a) ABBF in measurement (b) space grade implementation of phase shifter (c) DBBF in measurement

D. Steering Speed

Due to the fact that low LEO satellites are moving relatively fast, the faster the beam is steered, the more time for communication is provided. In terms of steering speed, both prototypes here are limited by the speed of the UART commands from the PC which is maximum 115200 baud rate. If digital controllers take over the steering algorithm, the speed will be much higher for both prototypes. The speed of steering is actually defined by the speed of updating all of the multiplier values. Off course, in DBBF, a Virtex-5 FPGA board with 100 MHz clock is able to change the virtual multipliers inside the FPGA within a few tens of nano seconds while, in ABBS, it takes slightly more (micro seconds) using state of the art microcontrollers. Luckily, speeds like this are far above our requirements.

VI. CONCLUSIONS

In this paper, the implementation of two basic types of beam forming, namely baseband digital and baseband analogue, have been compared. Phase shifter implementation, as a key part of the phased array, has been explained. The architectures of two basic 1×2 prototypes have been discussed. The most important factors characterizing an array antenna working in space, which are space qualification, price, power consumption, size, flexibility, and speed of steering, have been compared.

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